REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED
10-05-2003	Final Report	01-05-1999 – 30-09-2002

4. TITLE AND SUBTITLE Undulatory Flap Propulsion – Reduction to Practice	5a. CONTRACT NUMBER
	5b. GRANT NUMBER N00014-99-1-0452
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Howle, Laurens, E., PhD	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Mechanical Engineering and Materials Science Dept. Duke University Durham, NC 27708-0300	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 800 Arlington, VA 22217-5000	10. SPONSOR/MONITOR'S ACRONYM(S) ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AILABILITY STATEMENT

Distribution Unlimited

20030523 146

13. SUPPLEMENTARY NOTES

14. ABSTRACT

We use computational and reduced-order modeling for predictive studies of undulatory propulsion systems. Through the understanding of the factors that affect the performance of undulatory swimmers, we optimize man-made devices that employ novel methods for propulsion such as undulatory flap propulsion.

15. SUBJECT TERMS

Marine propulsions, swimming, flapping flight, vortex dynamics

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18 NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclass.	Unclass.	Unclass.	UL		Howle, Laurens E.
					19b. TELEPHONE NUMBER (Include area code) 919-660-5331

FINAL REPORT

GRANT #: N00014-99-1-0452

PRINCIPAL INVESTIGATOR: Laurens E. Howle, Ph.D.

INSTITUTION: Duke University

GRANT TITLE: Undulatory Flap Propulsion - Reduction to Practice

AWARD PERIOD: 1 May 1999 - 30 September 2002

OBJECTIVE: Our objective is to use computational and reduced-order modeling for predictive studies of undulatory propulsion systems. Through the understanding of the factors that affect the performance of undulatory swimmers, we optimize man-made devices that employ novel methods for propulsion such as undulatory flap propulsion.

APPROACH: We use efficient reduced-order computational methods to simulate and analyze propulsive motions used by biological undulatory swimmers. Our particular focus of analyzing undulatory swimmers is to gain a quantitative understanding of thrust generation and propulsive efficiency of the motions used by these biological swimmers. Certain Navy-specific applications such as stealthy propulsion and high maneuverability or station holding capability in a turbulent environment are especially well suited for undulatory propulsion. We study in detail the limitations of adapting biological undulatory propulsive motions to mechanical devices. Through advanced numerical modeling, we distill the motions of biological swimmers into the simplest mechanical systems capable of reasonable propulsive performance.

ACCOMPLISHMENTS: During this research project, we have

1. created a two-dimensional vortex-lattice model of two undulatory propulsors with wake-sheet interference and analyzed the force generation due to wave-sheet interference
2. created a three-dimensional vortex ring model of undulatory flap propulsion of a blunt unmanned underwater vehicle,

3. created a vortex-lattice computational model to analyze the time history of force generation of a compliant lifting structure (for example, a flexible wing or rudder) in the presence of a turbulent environment,
4. created a vortex-lattice computational model to analyze hysteresis and flutter instability of a compliant surface in a uniform flow field,
5. created a vortex-lattice computational model to most closely match the body motions of a biological swimmer (fish) with a rubber nektor,
6. analyzed the fitness of commonly used fish body wave shape amplitude envelopes
7. created a computational fluid dynamics model to find the optimal time-history for flapping flight
8. and conducted wind tunnel tests of the hydrodynamic influence of leading edge tubercles found on humpback whale flippers.

CONCLUSIONS: Our modeling of flap propulsion of blunt unmanned underwater vehicles reveals that flow streamline distortion created by the presence of the blunt hull *significantly* alters the performance of the flap propulsor. Therefore, one most optimize the shape of flap propulsors in the perturbed flow field. This finding will increase the workload for our future designs but will help us to generate flap geometries with greater efficiency. An additional finding of this work is that the optimal vortex sheet distribution places the majority of the shed vorticity at the extremes of the flap tail flight path.

In studying the force generation history of a fixed flexible lifting surface (such as a flexible wing or rudder) in the presence of a turbulent environment, we find that structure flexibility reduces impulsive loads created by gusts but dues not significantly alter induced drag. However, one must take case to avoid the flutter instability.

Our analysis of rubber nektor actuation is designed to find the input driving schedule, materials properties and nektor body shape that most closely mimics the body undulations of a swimming fish. We find that heave actuation (lateral displacement) is critical in matching body shape.

Several simple equations are commonly used in the literature to describe the undulatory waves fish pass down their bodies for aquatic propulsion. Muscle actuation is found to propagate with extremes of curvature rather than lateral displacement. Further, the speed with which the extremes of curvature and displacement travel down the fish body are non-constant. Our analysis the equations used to describe fish motion reveals that most do not capture the proper phase velocities of extremes of displacement and curvature.

The leading edge of humpback whale (*Megaptera Novaeangliae*) flippers have a scalloped appearance unique among marine mammals. Our precision wind tunnel measurements of idealized scale models of humpback whale flippers with and without tubercles (scalloped shape) shows that the presence of the tubercles delays the angle of attack at which stall develops by approximately 40 percent. This increase in stall angle is accompanied by increased lift and without a significant increase in drag.

SIGNIFICANCE: The basic research portion of the project will aid bio-locomotive studies of swimming creatures. Our analysis the kinematic equations of fish bodies will provide more accurate equations for describing the motion of fishes.

Through our analysis of undulatory flap propulsion, we will contribute to the scientific community a detailed understanding of the interactions of structures and fluid during propulsion. This will aid others in designing hybrid propulsion devices.

The increased lift and delayed stall enabled by a scalloped leading edge of a lifting surface offers an alternative to vortex generators used on aircraft wings. This might benefit high-performance lifting surfaces for low Reynolds number autonomous aircraft and for automomous underwater vehicle operation.

PATENT INFORMATION: None.

AWARD INFORMATION: Promoted to Associate Professor (with tenure). Promoted to Director of Graduate Studies.

PUBLICATIONS AND ABSTRACTS:

1. Howle. L.E. "Undulatory flap propulsion". *Proc. 11th Symp. Unmanned Untethered Submersible Technology*. 1999.
2. Murray, M.M. *Hydroelasticity Modeling of Flexible Propulsors*. Ph.D. Dissertation. Duke University. 1999.
3. Martin, J.I., Howle, L.E. & Murray, M.M. "Optimization of undulatory flap propulsors". *Proc. 12th Symp. Unmanned Untethered Submersible Technology*. 2001.
4. Moore, N.J., Howle, L.E. & Murray, M.M. "Controlling the output wave shape during undulatory swimming". *Proc. 12th Symp. Unmanned Untethered Submersible Technology*. 2001.
5. Murray, M.M. & Howle, L.E. "Response of compliant foils to dynamic loadings produced by oncoming vorticies". *Proc. 12th Symp. Unmanned Untethered Submersible Technology*. 2001.
6. Martin, J.I. & Howle, L.E. "Undulatory propulsion of a blunt body". *Dynamics Days 2001 Abstracts*.
7. Moore, N.J. & Howle, L.E. "Numerical analysis of aquatic propulsion". *Dynamics Days 2001 Abstracts*.
8. Martin, J.I. *Optimization of Undulatory Flap Propulsors*. M.S. Thesis. Duke University. 2002.
9. Moore, N.J. *Minimizing the Error Between an Undulating Foil and a Swimming Fish*. M.S. Thesis. Duke University. 2002.
10. Murray, M.M. & Howle, L.E. "Spring stiffness influence on an oscillating propulsor". *Journal of Fluids and Structures*. In press. 2003.
11. Miklosovic, D. S., Murray, M. M., Howle, L. E. & Fish, F. E. Leading Edge Tubercles Delay Stall on Humpback Whale (*Megaptera Novaeangliae*) Flippers. *Nature*. Submitted. 2003.